THE PAVERS® SYSTEM:
A TOOL FOR THE (RE-)DESIGN OF FLEXIBLE AND RIGID PAVEMENT

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ABSTRACT

The need of a practical yet paramount pavement design and assessment software tool that can be used for back-calculating and forward calculation of both *flexible and rigid* structural pavement parameters led to the development of the software tool PAVERS ®. It is a complete software package for the analytical design and assessment of rigid and flexible pavements. It allows the pavement engineer to define or use *calibrated* failure criteria for *all* pavement layers and subgrade in his pavement design and H/FWD assessment projects. The effect of different pavement materials, strengths, load or complex load mixes can quickly be explored.

INTRODUCTION

The arrival of "New Generation Aircraft" (NGA) such as Boeing's 777 and Airbus’s A380 has generated wide-spread concern about the effect of Multiple Wheel Load Interaction on the response and performance of rigid and flexible pavements. The requirement to understand pavement performance has resulted in an demand for accurate site testing systems that will allow accurate prediction of pavement deterioration with time and will ensure that any deterioration of the pavements is identified as early as possible so as to minimize the requirement for major reconstruction work. Implementation of calibrated design criteria into user-friendly software tools allows the designer to access the full advantages of the layered elastic method *and* multi-layer rigid plate models, including treatment of wander, and quickly produce designs for complex aircraft mixes and layered structures that are consistent with the original design concept. It is true: over the last decades, a lot of progress has been made in the implementing pavement design in to a computer environment. The giant leap in computer power has led to the development of comprehensive computer models often developed as a three-dimensional finite element model (3D-FEM). The latter appears to be elaborate, but is often too time consuming for use in real life assessment projects. The need of a practical *and* paramount (re-)design and FWD based assessment tool led to the development of the software tool PAVERS®, which is an acronym for PAVement Evaluation and Reporting Strength.

PAVEMENT (RE-)DESIGN CONCEPT

The philosophy of the analytical approach to pavement design is that the structure should be treated in the same way as other civil engineering structures, the procedure for which may be summarized as follows:

1. Specify the loading.
2. Estimate the size of components.
3. Consider the materials available.
4. Carry out a structure analysis using theoretical principles.
5. Compare critical stresses, strains or deflections with allowable values.
6. Make adjustments to material or geometry until a satisfactory design is achieved.

7. Consider the economic feasibility of the result.

This contrasts with the traditional method of designing pavements which is based on experience and the use of a test (the CBR) on the subgrade. Application of such empirical methods is restricted to the conditions under which the experience was obtained. It is because of the complexities of structural behavior and material properties that empirical procedures have endured for so long in pavement engineering. However, with the knowledge now available from research, a procedure similar to that outlined above can be applied to asphalt and rigid pavements. Conversely, for a pavement of known thickness constructed on a subgrade of identifiable characteristics, it is possible to determine the loads that the pavement can safely carry. This method of evaluating the load-bearing capacity is known as the ‘reverse-design method’. This method is used for the reversed design or evaluation of pavements.

DESIGN CONCEPT FOR FLEXIBLE PAVEMENT

Over the years a gradual transition took place moving from empirical pavement design methods to rational design concepts using mechanistic-empirical calibration concepts. However, in airport pavement design the CBR method is still frequently used. The US Army Corps of engineers CBR method (Method S77-1) for the design of aircraft pavements was calibrated against full-scale trafficking test on unbound pavements conducted 30 years ago. This method used single layer analysis and therefore had no direct mechanism for measuring the superior load spreading characteristics of the bound layers. Bound layers were increasingly being used, however, and were typically accounted for within the empirical design by using layer equivalency factors.

The Burmister layered elastic method was introduced into regular design practice for flexible pavements in the mid-1990's, with the release of the computer program LEDFAA by the U.S. Federal Aviation Administration (FAA 1995b), the Australian-developed program APSDS (Rickards 1994) and also the PAVERS® program (Stet et al 2001 & 2004). These tools facilitated the treatment of bound layers, eliminated the need for the 'equivalent single wheel load', and removed the requirement for 'design aircraft'. The flexible multi-layer model in PAVERS® is a classical linear elastic Burmister multi-layered structure. The layers are isotropic except for the bottom layer where anisotropy is addressed by different moduli in the horizontal and vertical direction. The interface between two adjacent layers can be varied between full friction to full slip using the BISAR or WESLAY definition. In the case of APSDS and PAVERS®, its method for dealing with aircraft wander meant that the pass-to-coverage ratio' was no longer required for asphalt pavements.

In design, pavement responses (stresses, strains and deflections) are used to estimate the development of pavement distress (rutting and fatigue cracking). Various standardized methods (FAA & ICAO), based on the CBR approach, do not provide a realistic representation of Multiple Wheel Load Interaction effects on pavement responses. The arrival of "New Generation Aircraft" (NGA) such as Boeing's 777 and Airbus’s A380 which is scheduled for 2006 has generated wide-spread concern about the effect of Multiple Wheel Load Interaction on the response (and performance) within empirical pavement design methods. It is believed that more advanced structural models are capable of better representing the response interaction from NGA landing gears, but these have not been verified with field data. In 1999 the FAA's National

Airport Pavement Test Facility initiated full-scale testing to establish design criteria for the current trend in NGA gears. Calibrated design criteria are also being developed at the A380 Pavement Experimental Program (A380 PEP) in Toulouse, France.

Mechanistic-empirical calibration can be done by using calibrated transfer functions which relate critical stresses and strains in a multi-layered (or rigid) pavement structure to an allowable number or load repetitions. No matter what the transfer function is used, it is important to carefully calibrate the function so that the predicted distress can match with field applications. In 1999 the FAA's National Airport Pavement Test Facility initiated full-scale testing to establish design criteria for the current trend in NGA gears. Calibrated design criteria are also being developed at the A380 Pavement Experimental Programme (A380 PEP) in Toulouse, France.

Implementation of calibrated design criteria into software tools allows the designer to access the full advantages of the layered elastic method, including treatment of wander, and quickly produce designs for complex aircraft mixes and layered structures that are consistent with the original design concept.

DESIGN CONCEPT FOR RIGID PAVEMENT

Rigid pavements are commonly modeled as a slab on-grade system. The well known Westergaard equations are still much appreciated as in most cases the edge stress condition is critical. The Westergaard model uses a dense liquid Winkler foundation model. In general the Westergaard-Winkler model overestimates the values of deflection and bending stress in a concrete slab. However, because of the ability to compute edge stresses, the attractiveness of Westergaard's solutions have never diminished.

The Pasternak foundation is a more realistic representation and encompasses the disadvantages of the Westergaard-Winkler and Burmister model. The introduction of a horizontal linkage, Pasternak's shear constant, in Winkler's model is a remedy for the discrepancies between Westergaard's theory and the multi-layer theory, while the great advantages of Westergaard's model (edge and corner loading) are maintained. The Pasternak Foundation model can be considered as a linked spring system. The model is an improvement of Westergaard's slab on a Winkler dense liquid foundation. The constant, k, defines the subgrade and/or foundation as in classical works of rigid pavements. The modulus of subgrade reaction on the slab is k times the deflection, and represents the reactive pressure to a load induced deflection. Pasternak’s parameter G can be seen as a horizontal spring, which is connected to Winkler's spring. For G=0, one arrives at Winkler’s foundation.

Since the limited slab dimensions and the support conditions of subgrade and joints are vital parts of the structural evaluation, CROW (1999) developed a single slab model that was capable of combining all advantages. Van Cauwelaert mathematically solved the problems for rectangular interior and edge loads in 1997. The boundary conditions of the theoretical model at the edge presume a difference in deflection between loaded and unloaded joint sides, thus allowing for some shear transfer through the joint (shear force left of the slab is equal to shear force of right slab side) and assumes no moment transfer through the joint (M=0). Based on Van Cauwelaert's closed form mathematical integral approach, codes for back-calculating and computing vertical stress on the foundation and the bending stresses at the bottom of the slab have been programmed.

The FAA recommends the use cemented bases when aircraft with an operating mass over 45 tons use the pavement. In principle the Westergaard solutions are only valid for slabs on granular bases. However, the Westergaard model is often used for cemented bases too. This conflicts with Westergaards solution which is based on the theory of thin plates: thin against other dimensions means a two-layered structures (slab on an infinite subgrade). McCoulough's transformation by computing an equivalent k-modulus is often used, but is only valid when the modulus of the layered materials is far smaller than the Young's modulus of the concrete. This is obviously not always the case when using cemented bases. A muli-layered slab model should be used instead. Van Cauwelaert's multi-slab model is based in equivalency of elasticity and allows partial friction at the interfaces of adjacent layers.

Thermal gradients also introduce stresses into a slab. Eisenmann's model seems not to be applicable on layered structures due to the postulation of constant contact of the layers (friction is possible, but full adhesion is a necessity). The theory of the determination of thermal stresses in a single or a multi-layered structure on a Pasternak foundation has been developed by Lemlin et al. [3]. The radii of curvature of the different layers can be different (variable gradient with depth, different thermal dilatations).

Back and forward calculation can be done for all slab coordinates and multiple loads placed on the rectangular slab. The slab support conditions, i.e. the foundation parameters are back-calculated taking the resonance Young's modulus of the concrete as fixed input. Multiple loads can be placed *anywhere on the slab*. Hence, back-calculation can be done for the center and edge position. The closed form mathematical solving technique allows to *use n-number of loads*, overcoming the ESWL concept which can be considered as one of the major draw backs of the classical Westergaard equations. The unique rigid model code allows to use the same method for dealing with aircraft wander as for asphalt pavements, eliminating the pass-to-load repetition concept for rigid pavements.

No matter how good the pavement and load models might be, mechanistic-empirical data is still required to tie the life of a pavement to the computed stress or strain response. It is important to carefully calibrate the function so that the predicted distress can match with field applications. Mechanistic-empirical calibration can be done by using calibrated transfer functions which relate critical stresses.

BACK-CALCULATING PAVEMENT

Measured deflections have to be translated into stresses or strains by back-calculation of the pavement structure. The basis of any analytical evaluation method is the structural pavement model employed. The back-calculation suite has an automatic back-calculation routine. Deflection basis and construction data can be read from Excel files. The program allows for back-calculating flexible and rigid pavement. For rigid pavement, the user can either back-calculate deflections at the slab interior or at the slab's joint. For the latter, the deflection transfer across the joint is required as an additional input value. The friction between two layers and the layer thickness can either be fixed or set variable in the back-calculation routine. For flexible pavements that is the determination of the distinct layer moduli of constructed layers and the subgrade from known layer thickness' and given seed moduli and boundary values. For illustration purposes. For rigid pavements the slab support conditions at the slab's edge or mid-span position are back-calculated. Figure 1 reports the results of back-calculating a deflection bowl measured at the slab's edge.

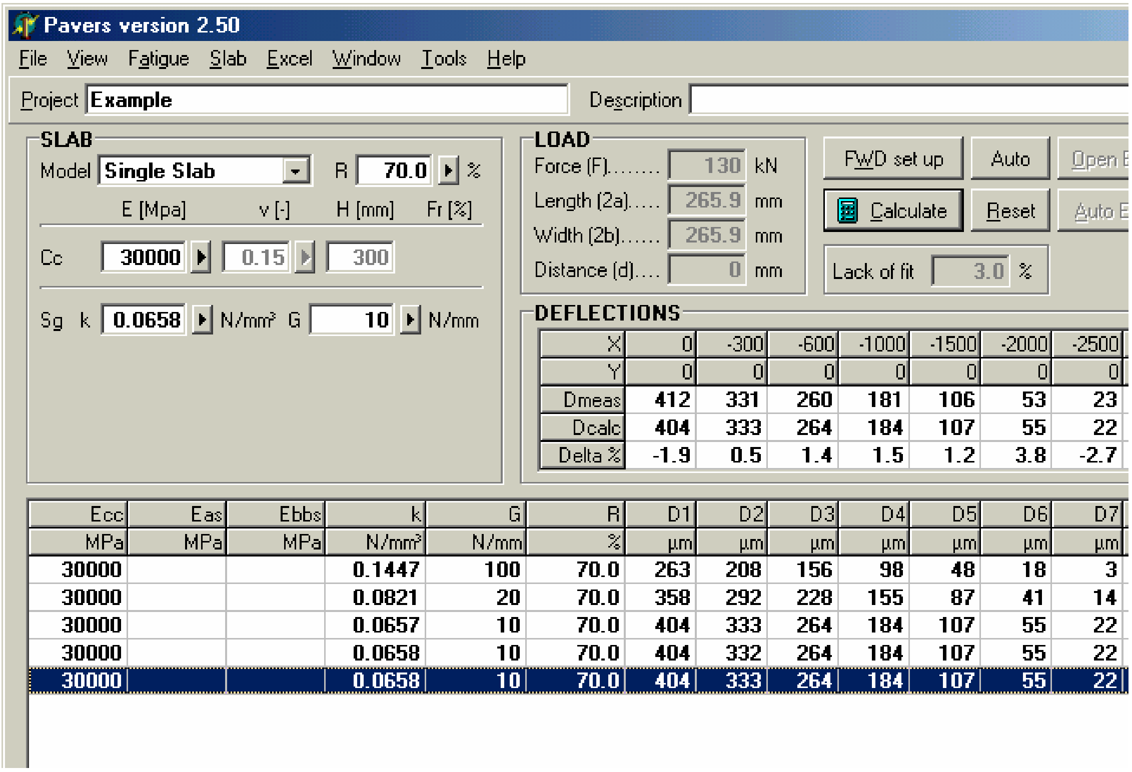

Figure. 1. Example of back-calculating rigid pavement for edge position

The structural pavement parameters is determined by comparing measured deflections with calculated deflections using the mathematical models. The structural pavement parameters e.g. the concrete slab and its foundation characteristics and the elastic moduli of distinct pavement layers in flexible pavements are derived from an iterative computer based technique in which a deflection bowl is calculated from assumed combinations of input values. The structural parameters are adjusted until the computed deflections and SCI under a given load agree closely with the corresponding measured deflections and surface curvature index (SCI). If the calculated deflection at each point matches the measured values to within a fit of 2%, no further refinement is required. The structural parameters obtained this way are considered representative for the pavement structure under consideration. The back-calculation is done for at least 30 slabs or flexible deflection points. Since the modulus of the concrete has a profound influence on the deflections, this value is assessed from resonance tests according to NEN-EN 13296. The method relates the dynamic Young's modulus and the longitudinal (compression) velocities α and the transversal velocity β in an infinite medium:

$$E_d = \rho * \alpha^2 * \frac{(1+\nu)*(1-2\nu)}{1-\nu} \quad \textit{and} \quad E_d = \rho * \beta^2 * 2\,(1+\nu)$$

In which,:

Ed	=	dynamic Young's modulus [Pa].
ρ	=	material density [kg/m3]
α	=	longitudinal velocity [m/s]
β	=	transversal velocity [m/s]
ν	=	Poisson ratio

The slab support parameters k and G are assessed in an iterative computer based technique in which a theoretical deflection basin is calculated and compared to the real deflection measured at site. The assessment is be performed on the data of all measured slabs. The model allows for back-calculating in the interior and edge position. For the latter use is made of the deflection ratio which is an input parameter defined as the deflection of the unloaded slab edge to the deflection at the adjacent loaded slab edge. An indication of the shear transfer (γ) at the edge is obtained from the deflection ratio For R=0 (γ=0) there is no load transfer and for R=1 (γ=1) there is full load transfer. The shear transfer at the slab edge is:

$$\gamma = \frac{2R}{1+R}$$

DESIGN AND RESIDUAL LIFE ASSESSMENT

Once the structural pavement parameters are assessed, the life (or bearing capacity) can be determined. For the calculation of the (residual) life, it is necessary to have details on the traffic (which has used the pavement in the past and also) to forecast the use of the pavement in the future. The user may compose his own load mix for evaluation out of a database with the load characteristics of PAVERS®. Loads can be selected from a database containing over 200 aircraft, industrial loads and trucks. Own loads can be entered into this database. The accumulated pavement damage is assessed by adding the damage of the load, taking into account the position of the loads on the pavement. PAVERS® calculates the most heavily loaded strip of the pavement due to a specific load mix on flexible and rigid pavement.

The residual pavement life is assessed by deducting the historical load repetitions from the initial allowable number of load repetitions corrected for lateral wander. The accumulated pavement damage is assessed by adding the damage of the aircraft, taking into account the position of the loads on the pavement. Wander effects are addressed with a normalized beta-distribution. The damage is the reciproke of the allowable number of aircraft passages. According to the Palmgren-Miner hypotheses, the structural pavement life is used when the cumulative damage number is equal to 1 and the residual life is nil. If the allowable number exceeds the number of historical repetitions, the residual life can be calculated based on the difference of allowable and past traffic, and the future traffic.

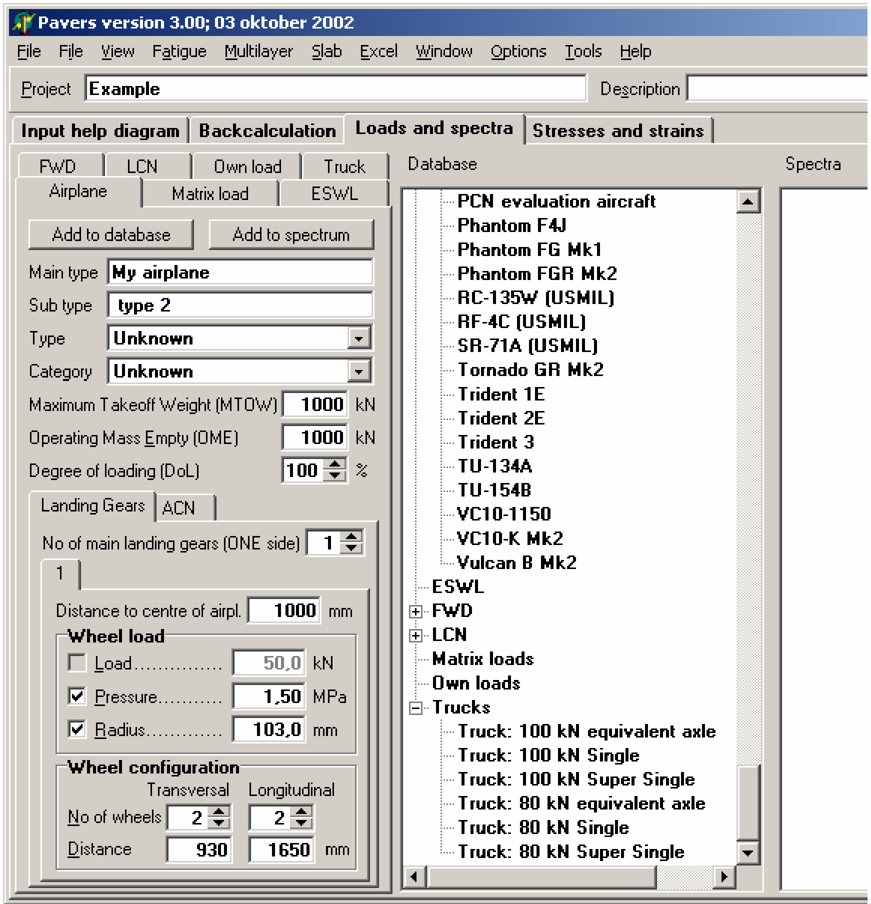

Figure 2. Loads can be selected from a database.

For the calculation of the residual life, it is necessary to have details on the traffic which has used the pavement in the past and also to forecast the use of the pavement in the future. Wander effects are addressed with a normalized beta-distribution (HoSang 1978). The complex frequency distribution and different gear loads are analytically transferred into a fatigue damage distribution of the pavement along different tracks and positions on the slab or flexible pavement. Accumulation of the effects of the number of load repetitions is made on the basis of Miner's damage hypothesis for all pavement materials, i.e. concrete, flexible layers, foundation subbase layers and subgrade. For cement concrete, the modulus of rupture must be determined for a number of cores. Based on the historical traffic data, present structural condition and traffic forecast, insight in future structural deterioration is gained. Accumulation of the effects of the number of load repetitions is made on the basis of Miner's damage hypothesis. The residual pavement life is assessed by deducting the historical load repetitions from the allowable number of load repetitions corrected for lateral wander. Accumulation of the effects of the number of load repetitions is made on the basis of Miner's damage hypothesis for all pavement materials, i.e. concrete, flexible layers, foundation sub-base layers and subgrade.

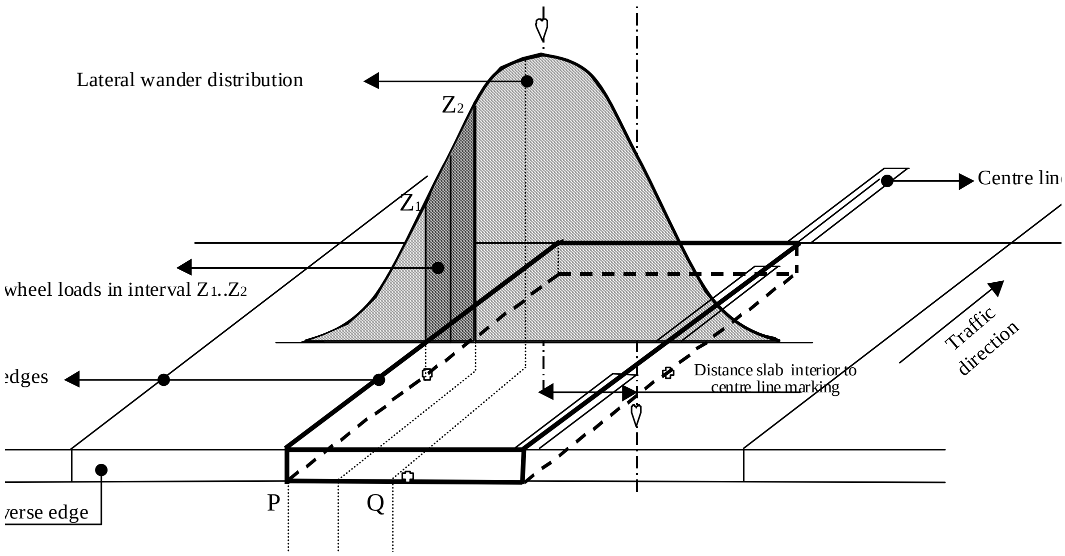

Figure 3. Lateral wander concept for rigid pavementAssessing pavement condition

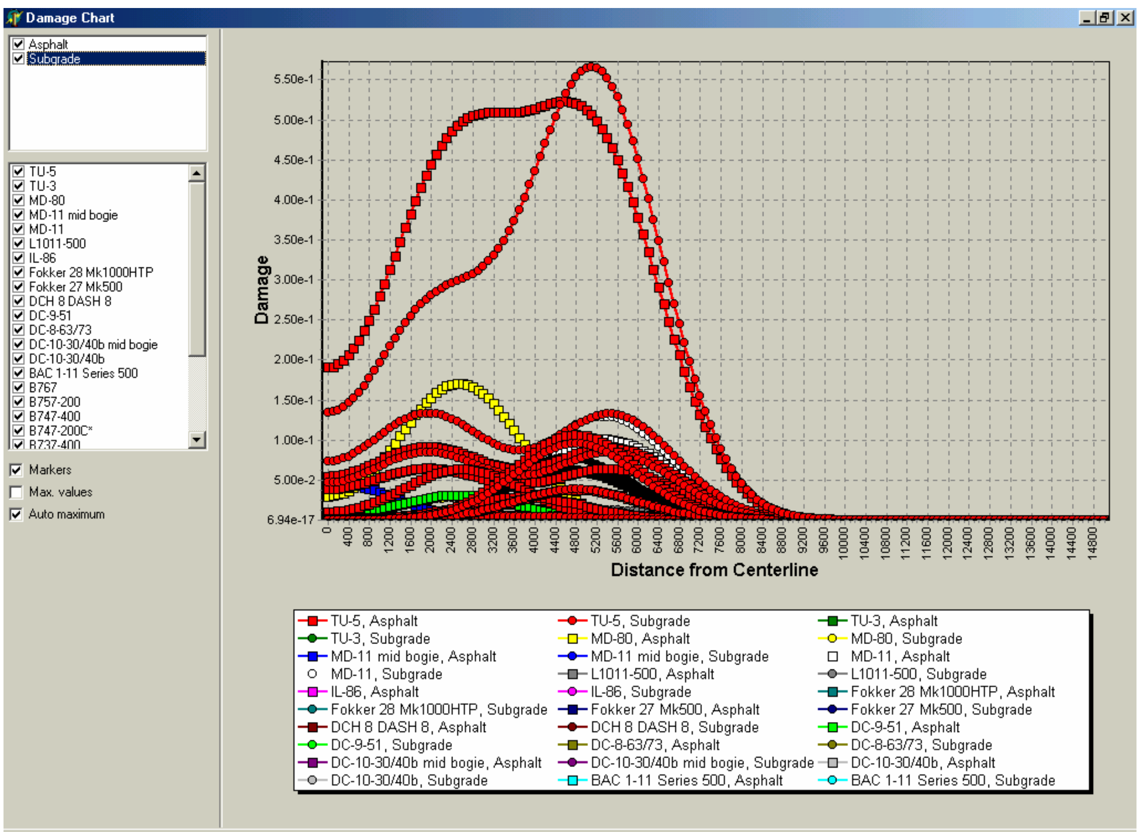

Figure 4. Lateral wander & pavement life assessment & thickness design of asphalt pavement

LOAD-CARRYING–CAPACITY OF AIRPORT PAVEMENT

PAVERS® enables the determination of a technical Load Classification Number (LCN) and the Pavement Classification Number (PCN). The former method is used by NATO. A universal system for civil airport pavements for determining the weight limitation of aircraft operating on airport pavements involves comparison of an airport's Pavement Classification Number (PCN) with an Airplane Classification Number (ACN). According to this world-wide ICAO standard, aircraft can safely operate on a pavement if their ACN is less than or equal to the pavement load bearing capacity or PCN. An aircraft having an ACN equal to or less than the PCN can operate without weight restrictions on a pavement. The PCN is formally published in an Aeronautical Information Publication (AIP).

STATEMENT OF CAPABILITIES

PAVERS® is a joint development and proprietary of dr. Frans Van Cauwelaert, Bert Thewessen and Marc Stet teaming up in Pavers.nl. Listed below are a number of novelties. This list is by no means comprehensive; it merely concentrates on the highlights of the software tool:

- Windows oriented help files clarifying the models and usage of the program. Microsoft in- and output. Deflection basin and construction data can directly be read from Excel files,

- It is important that all pavement materials of the distinct layers are evaluated in a design process. The tool allows to set design criteria to all pavement layers and subgrade. The user can define his criteria or select the appropriate criteria from a database for cement concrete, asphalt concrete, bound base materials or subgrade type,

- Automated back-calculation routine for bulk processing of flexible pavement data. The back-calculation part is compatible with Dynatest, Carlbro (formerly Phönix), JILS and Komatsu deflectometer devices, which operate with a pulse duration of about 25 milliseconds. For KUAB deflectometers, with a pulse duration of approx. 60 ms a conversion for pavements on a weak subgrade is necessary. Coefficients to convert KUAB deflections into deflections with smaller pulse duration for specific geophone locations are given.

- A versatile routine to fix input parameters (e.g. percentage of slip, thickness, Young's moduli) in the back-calculation process,

- Database with 'known' fatigue relations for asphalt, cement concrete, cemented base materials, sub-bases and subgrade. The user can either select one of the many predefined relationships or input the constants of the transfer function using a tool to determine the constants of the asphalt fatigue relationships,

- A database containing over 200 aircraft with details on gear geometry, load and ACN data and a routine to accommodate LCN/LCG, ACN calculation according to ICAO Annex 14 and PCN assessment according to ICAO's runway strength rating system.

- The lateral wander concept is employed in asphalt pavements to determine the heaviest trafficked pavement strip and to determine the most critical joint in a rigid pavement. The different tracking paths of aircraft types relative to pavement centerline are taken into account. Any degree of wander can be specified and the effect of wander is rigorously treated, eliminating the need of the pass-to-cover-ratio concept,

- Statistical tools for the required number of H/FWD measurements and the Bootstrap,

- Several helpful tools: a/o tools to determine plate foundation parameters, a tool to assess fatigue transfer functions and graphs to present results etc.

SHARING KNOWLEDGE

PAVERS® was created to give pavement specialists a definite tool for the structural design and evaluation of road, airport and industrial rigid and flexible pavement. Sharing knowledge is central to the philosophy of the developers of PAVERS® and a registered membership of the User Group is automatic upon purchase of the system (Stet et al 2001). As a User Group member, one can help decide what the next improvement to the program will be. License fees are essential to improve the program. To cater for the on-going development a reimbursement is asked. Registered members get periodic updates of the program at handling costs. Visit www.aperio.nl or www.pavers.nl for a free download of the models and design theories or to request an evaluation copy by e-mail.

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